ESTIMATION OF PATH-AVERAGE EVAPORATION AND PRECIPITATION USING A MICROWAVE LINK

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Abstract

The potential of a 27 GHz microwave link for measuring both evaporation and precipitation is investigated. For the estimation of evaporation a combination of the microwave link (radio wave scintillometer) and an energy budget constraint is proposed. This Radio Wave Scintillometry-Energy Budget Method (RWS-EBM) has been tested using data from an experiment with a 27 GHz radio wave scintillometer over 2.2 km and four eddy covariance (EC) systems. Comparing one day of measurements (30-minute intervals) of the evaporation estimated using the RWS-EBM to those measured by eddy covariance systems leads to the conclusion that the method provides consistent estimates under relatively wet conditions.

In the case of precipitation, analyses show that the specific attenuation of an electromagnetic signal at 27 GHz varies nearly linearly with the rainfall intensity, which is ideal for line-integrating instruments. Data from an experiment with a 4.89 km microwave link and a line configuration of seven tipping-bucket raingauges are used to test whether this instrument is indeed suitable for the estimation of path-average rainfall. Results from this experiment show that the attenuation due to wet antennas can have a significant effect on the retrieved rainfall intensity. However, when a two-parameter wet antenna correction function is applied to the link data, comparisons with the raingauge data show that the instrument is indeed well-suited for the measurement of path average rainfall.

1. INTRODUCTION

Measurement of the water fluxes (both upward and downward) between the land surface and the atmosphere at scales around 1 km is of vital importance to both hydrology and meteorology [e.g. Parlange et al., 1995, Su, 2002, Berne et al., 2004]. A microwave link has the potential to measure both evaporation and precipitation [Leijnse et al., 2006a,b] on spatial scales of a few km with a high temporal resolution.

A microwave link consists of a transmitter and a receiver, between which an electromagnetic signal (in the microwave band) propagates. When there is no rain, evaporation can be estimated from the interaction of the signal with the turbulent eddies in the atmospheric boundary layer. In the case of rain, the precipitation can be estimated from the portion of the signal that is scattered and/or absorbed by the raindrops.

For the measurement of evaporation, the microwave link is used as a scintillometer [see the editorial by de Bruin, 2002, and references therein]. The principle is that the turbulent eddies that transport heat and water vapor cause the received signal to scintillate through time-varying local gradients in the refractive index of the air. The magnitude of the fluctuations of this refractive index (expressed as its structure parameter C_n^2) can be used to calculate the flux of water vapor. A relation derived by Tatarskii [1971] can be used to calculate C_n^2 from the received signal. The estimation of evaporation from this C_n^2 is discussed in Sec. 2.

The amount of attenuation experienced by an electromagnetic signal travelling through rain can be used to determine the rainfall intensity. How the rainfall intensity is estimated from this path-integrated attenuation is discussed in Sec. 3.

2. EVAPORATION

To estimate the evaporation from the structure parameter of the refractive index of air, a system of equations needs to be solved. This system consists of the relation between different structure parameters, the Monin-Obukhov Similarity Theory and the surface energy balance and is called the Radio Wave Scintillometry-Energy Budget Method (RWS-EBM). These relations will be discussed in Sec. 2.1. Experimental results will be used to verify the method in Sec. 2.2.

2.1. **Method.** The refractive index of air n (-) is affected by that of dry air, the water vapor present in this air, and the proximity of the signal frequency to an absorption line of water vapor. As a result it depends on the temperature T (K), the absolute humidity Q (kg m^{-3}) and the pressure p (Pa) of the air. Hill et al. [1980] give a relation between the structure parameter of the refractive index of air and the structure parameters of temperature C_T^2 (K^2 m$^{-2/3}$) and moisture C_Q^2 (kg^2 m$^{-20/3}$)

$$C_n^2 = A_T^2 \frac{C_T^2}{T^2} + A_Q^2 \frac{C_Q^2}{Q^2} + 2A_T A_Q \frac{C_{TQ}}{TQ}, \tag{1}$$

where the contribution due to pressure fluctuations is neglected. Following the suggestion by Kohsiek and Herben [1983], the cross-structure parameter of temperature and humidity C_{TQ} (K kg m$^{-11/3}$) can be written as $C_{TQ} = r_{TQ} C_T C_Q$, in which r_{TQ} is the correlation coefficient between the temperature and humidity fluctuations. The dimensionless sensitivity coefficients of the refractive index A_T and A_Q at radio wavelengths longer than 3 mm [Hill and Clifford, 1981, Andreas, 1989] depend only on the temperature and humidity.

The Monin-Obukhov Similarity Theory is valid in the surface layer of the atmosphere, and describes the profiles of momentum and conservative scalars. MOST can be used to relate the structure parameters C_T^2 and C_Q^2 at a given height in the surface layer to the sensible (H_s) and latent ($L_v E$) heat fluxes (both in W m^{-2})

$$\frac{\rho^2 c_p^2 C_T^2}{H_s^2} = \frac{L_v^2 C_Q^2}{(L_v E)^2} = \frac{1}{u_*^2 (z_L - d_0)^{2/3}} f_{Ob} \left(\frac{z_L - d_0}{L_{Ob}} \right) \tag{2}$$

where the specific heat of air at constant pressure is $c_p \approx 1005$ J kg^{-1} K^{-1}, u_* (m s^{-1}) is the friction velocity, z_L (m) is the height above the terrain, d_0 (m) is the displacement height of the turbulent boundary layer and ρ is the density of moist air. The Obukhov length L_{Ob} (m) is a measure of the stability of the surface layer, and depends on the rougness length of the terrain z_0 (m), the friction velocity and the magnitude of the heat fluxes H_s and $L_v E$. The friction velocity depends on the wind velocity u (m s^{-1}) measured at a height above the terrain z_u (m), the roughness length of the terrain and the stability of the surface layer, expressed by L_{Ob}. Hence, L_{Ob} and u_* need to be solved iteratively. The shape of f_{Ob} can be derived from the relations given by Businger et al. [1971]. For unstable conditions ($L_{Ob} < 0$ m), which are the only conditions considered in this paper, this function is

$$f_{Ob}\left(\frac{z_L - d_0}{L_{Ob}}\right) = c_1\left(1 - c_2\frac{z_L - d_0}{L_{Ob}}\right)^{-2/3}. \tag{3}$$

The constants $c_1 = 4.9$ and $c_2 = 7.0$ were empirically derived for C_T^2 profiles by Wyngaard et al. [1971] and the latter was later corrected to $c_2 = 6.1$ by Andreas [1988].

The system of equations presented above can be closed by using the principle of conservation of energy, which requires the sum of the latent and sensible heat fluxes to be equal to the total available energy

$$L_vE + H_s = R_n - G, \tag{4}$$

where R_n (W m^{-2}) is the net radiation and G (W m^{-2}) is the ground heat flux (both positive when downward).

If we assume $r_{TQ} = 1$, the number of equations (four: Eqs. (1), (2) and (4), where Eq. (2) represents two equations) equals the number of unknowns (four: C_T^2, C_Q^2, H_s and L_vE) so that the turbulent fluxes can in principle be solved using measurements of C_n^2 and $R_n - G$, albeit implicitly.

2.2. **Experimental results.** The Flevoland experiment was carried out by Meijninger et al. [2002a,b] in the southern part of Flevoland, The Netherlands, between July 18 and August 20, 1998. This was a relatively wet period, in which the evaporation was close to potential most of the time. A 27 GHz scintillometer system with 0.6 m diameter antennas, manufactured at the Eindhoven University of Technology, was used for this experiment. It was mounted on two wind turbines, placed 2.2 km apart, at a height of 10.9 m (both the transmitter and the receiver). All measured variables were averaged over 30-minute periods in this experiment.

The heat fluxes that affect the scintillometer signal originate from uniformly distributed rectangular plots with dimensions of approximately 0.5 km, where potatoes, sugar beets, wheat or onions are grown. Each of the four crop types covers approximately 25% of the total area around the scintillometer. The effective roughness length z_0 and displacement height d_0 were estimated by Meijninger et al. [2002b] to be relatively uniform at 0.06 m and 0.32 m, respectively.

In four of the plots (each with a different crop type), eddy covariance (EC) systems were installed to independently measure the heat and momentum fluxes. In addition to these EC measurements, net radiation and ground heat flux were measured at each site. Although this is not a major issue, weights have been assigned to the fluxes measured by the EC systems according to the wind direction and a footprint analysis [Meijninger et al., 2002b].

The wind velocity u used in this section was measured at $z_u = 3.9$ m, and the temperature T and humidity Q were measured at 3.1 m at the sugar beet site. Because there will usually be only one point at which meteorological variables are measured in an operational setting with a stand-alone radio wave scintillometer, the total available energy

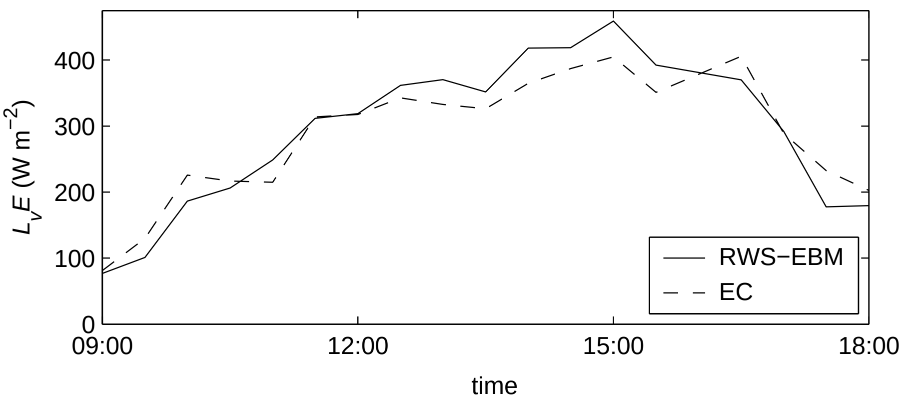

FIGURE 1. Time series of the latent heat fluxes determined using different methods on July 27, 1998.

$(R_n - G)$ used in this study is also the one that has been measured at the sugar beet site. The atmospheric pressure was not measured during the Flevoland experiment. We assume it to be constant at a value of $p = 101.3$ kPa.

The scintillometer data used in the comparison are those recorded during daytime (between 9:00 and 18:00) on July 27, 1998. Figure 1 shows the evolution of the latent heat flux measured by the EC systems and that estimated by the RWS-EBM on July 27, 1998. It can be seen that the latent heat fluxes estimated using the different methods are similar, which leads to the conclusion that the RWS-EBM reasonably captures the evaporation dynamics on this day in the Flevoland experiment.

3. PRECIPITATION

The relative decrease in power between the source of an electromagnetic signal (the transmitter) and a point in space (at a distance r from this source) due to attenuation by rainfall is quantified by the path-integrated attenuation $A_m = \int_0^L k(s)\mathrm{d}s$ (in dB). L is the link length, $k(s)$ is the specific attenuation (dB km^{-1}) at position s. The objective is now to estimate path-average rainfall intensity $\overline{R}$ from the measured path-integrated specific attenuation $\overline{k}$, using a relation between k and R.

3.1. **Method.** The specific attenuation and the rainfall intensity can both be computed by integrating the drop size distribution (DSD) $N(D)$ (m^{-3} mm^{-1}), weighted by appropriate functions [e.g. Atlas and Ulbrich, 1977]

$$k = \frac{10^{-2}}{\ln(10)} \int_0^\infty Q_{ext}(D) N(D) \mathrm{d}D \tag{5}$$

$$R = 6 \times 10^{-4} \pi \int_0^\infty D^3 v(D) N(D) \mathrm{d}D, \tag{6}$$

where the prefactors are related to the conversion of units, $Q_{ext}(D)$ (mm^2) is the extinction cross section of a drop with volume-equivalent diameter D (mm) and $v(D)$ (m s^{-1}) is its terminal fall velocity. The $v(D)$ relation used in this paper will be that of Beard [1976], which is considered to be the most accurate parameterization of raindrop terminal fall velocity in still air available to date. For a 27 GHz signal, the wavelength ($\lambda \approx 11$ mm) is of the same order of magnitude as the size of the scattering particles (raindrops). Therefore Mie scattering theory [e.g. van de Hulst, 1957] must be used to compute $Q_{ext}(D)$, which also depends on the rain temperature and the frequency of the signal.

As has been shown by many in the past [e.g. Atlas and Ulbrich, 1977, Olsen et al., 1978], the $k-R$ relation can be approximated by a power law

$$k = aR^b. \tag{7}$$

Using the 446 drop size distributions (where $R > 0.1$ mm h^{-1}) measured by Wessels [1972] in the period between January 3, 1968 and March 13, 1969 in De Bilt, The Netherlands, a non-linear power law fit of k to R can be performed. For a rain temperature of 288.15 K, the coefficient and exponent of this power law are found to be $a = 0.132$ and $b = 1.074$, respectively. From the proximity of b to one, it can be concluded that the relation between k and R is nearly linear for these data, and that in any case the exponent of this power law relation is significantly closer to one than those of power law relations used for remote sensing of rainfall using weather radar [Smith and Krajewski, 1993].

Olsen et al. [1978] list the coefficients and exponents of power law approximations of the relations between specific attenuation and rainfall intensity for different frequencies, temperatures and classically used drop size distribution climatologies. The exponents are all relatively close to 1, also indicating a nearly linear $k-R$ relation.

The near-linearity of the $k-R$ relation for different drop size distributions is the result of the fact that the integrands of Eqs (5) and (6) have similar shapes, as was suggested by Atlas and Ulbrich [1977]. This implies that the $k-R$ relation should be nearly independent of the DSD. An important result of the near-linearity of the $k-R$ relation ($k \approx cR$) is that the path-integrated attenuation A_m can be directly related to the path-average rainfall intensity $\overline{R}$

$$A_m = \int_0^L k(s)\mathrm{d}s \approx c \int_0^L R(s)\mathrm{d}s = cL\overline{R}.$$

Frozen precipitation falls outside the scope of this paper, but it is important to realize that it can occur and significantly affect the $k-R$ relation. In the remainder of this paper, the $k-R$ relation based on the DSDs measured by Wessels [1972] ($a = 0.132$ and $b = 1.074$) will be used.

3.2. **Experimental results.** An experiment with the same microwave instrument as the one used in Sec. 2.2 was conducted between the towns of Rhenen and Wageningen (4890 m), The Netherlands in the period from May 28, 1999 to July 23, 1999. The antennas of the system were mounted 46 m (transmitter) and 19 m (receiver) above the terrain. The bars over $\overline{R}$ and $\overline{k}$ to denote path-averages will be dropped in this section for simplicity of notation.

The microwave link signal is sampled at a rate of approximately 18 Hz. A line configuration of seven tipping-bucket rain gauges was used to independently estimate path-averaged rainfall intensity. The rainfall intensity measured by the gauges is averaged according to their distance to the nearest working neighbors or to the transmitter or receiver.

In rain, both antennas of the microwave link system may become wet, causing additional attenuation. Wet antenna correction algorithms like that described by Kharadly and

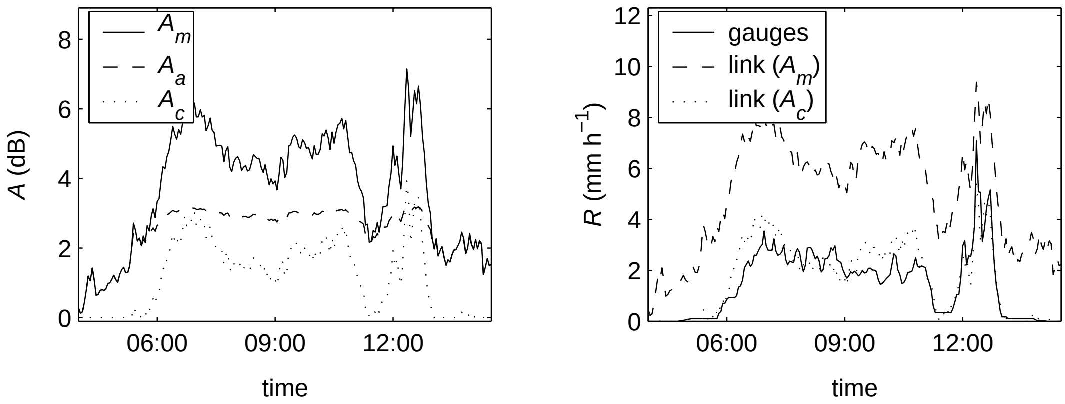

FIGURE 2. Attenuation and rainfall intensity measured the link, compared to the rainfall measured by the gauges. Also shown is the wet antenna attenuation (A_a) and its correction (A_c), on June 5, 1999.

Ross [2001] and extended by Minda and Nakamura [2005] for slow drying of antennas can only be applied here by using the raingauge data because the antennas were not calibrated for water film attenuation. Calibrating the wet antenna attenuation functions results in functions that are independent of time (as the antennas dry very quickly). The attenuation caused by the wet antennas A_a (dB) as a function of the measured attenuation A_m (dB) is assumed to have a negative exponential form $A_a = C_1(1-\exp(-C_2 A_m))$, with $C_1 = 3.32$ dB and $C_2 = 0.48$ dB^{-1}. Hence, the maximum wet antenna attenuation is 3.32 dB, which leads to a maximum overestimation of the rainfall intensity of 3.9 mm h^{-1} (occurring at $R = 11.6$ mm h^{-1}) if no wet antenna correction is applied. The measured attenuation can be corrected for the wet antenna attenuation using $A_c = A_m - A_a$ from which the corrected specific attenuation $k_c = A_c L^{-1}$ can be computed.

Figure 2 shows time series of the attenuation and rainfall intensity for an event on June 5, 1999. The measured attenuation is shown along with the estimated wet antenna attenuation and the corrected attenuation to give an idea of the magnitude of this correction. For the rainfall intensity, the microwave link estimate of the rainfall intensity with and without the wet antenna correction is compared to the gauges-estimated rainfall. It can be seen that the rainfall intensity estimated by the link without taking into account the wet antenna attenuation is dramatically larger than that estimated by the gauges. Application of the wet antenna correction yields far better results. Because this wet antenna correction depends on the raingauge measurements, it could be argued that the rainfall intensity estimated using k_c and that estimated from the gauges are not independent. However, considering the fact that the wet antenna correction is based on only two parameters, fitted for the entire event, the comparison does provide a good basis on which to test the potential of the instrument to measure precipitation. The dynamics of the rainfall intensity estimated by the gauges and by the link are seen to be very similar for this event. Hence, we can conclude that if the baselevel of the microwave link signal is known, the microwave link can estimate path average rainfall at a high temporal resolution relatively accurately.

4. CONCLUSIONS

A new method has been presented that uses radio wave scintillometer measurements in combination with measurements of the total available energy to estimate the latent heat flux, and hence the evaporation: the Radio Wave Scintillometry-Energy Budget Method (RWS-EBM). The application of RWS-EBM to experimental data collected in southern Flevoland, the Netherlands in the summer of 1998 yields good results when compared to independent EC measurements of the latent heat flux. It can be concluded from these experimental results that the proposed method works very well, at least for relatively wet conditions. More experimental research needs to be done to investigate the performance of the RWS-EBM under drier conditions.

The potential for a microwave link to measure path-average precipitation has also been investigated. As shown by other investigators in the past, the relation between the attenuation measured by the microwave link system and the rainfall intensity is seen to be nearly linear at 27 GHz. A power law $k - R$ relation with coefficient $a = 0.132$ dB km^{-1} (mm h^{-1})$^{-b}$ and exponent $b = 1.074$ has been derived from more than a year of measurements of DSDs in The Netherlands, and has been used in this paper.

Results of an experiment carried out in the summer of 1999 in the center of the Netherlands have been used to test whether a microwave link can be used to estimate precipitation. Analyses of data recorded by a microwave link system and a line configuration of seven raingauges show that it is extremely important to either calibrate the antennas for wet antenna attenuation or to avoid wetting of the antennas in the first place. We have calibrated the antennas for wet antenna attenuation using a relation from the literature and data recorded by the raingauges. The path-average rainfall intensity estimated using the resulting corrected specific attenuation is shown to represent that estimated by the gauges well, both in magnitude and in dynamics. From these results, we conclude that a microwave link can be used to measure precipitation if it is installed correctly.

Finally, we can state that a microwave link has great potential for measuring both evaporation and precipitation.

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